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Temporal and spatial relationship between sediment grain size and beach profile

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Abstract

Sediment samples and beach profile evolution data collected along one profile line at "El Puntal" Spit, Santander, Spain, are used to analyze the spatial and temporal structure of the grain size distribution variability and its relationship with the beach profile changes. Standard principal component analysis (PCA) and three-way PCA is applied to determine the temporal and spatial scales of variability of the data.

Results indicate that the sediment grain size distribution varies markedly along the beach profile both spatially and temporally. These variations are shown to be strongly related to morphological changes in the beach profile. The spatial eigenvectors determined from the profile data and those from the sediment data exhibit similar patterns with their maxima and minima located at the same position. Since eigenvectors may be regarded as representative of uncorrelated modes of variability it is concluded that the spatial variability of both sediment and profile data are strongly related. In particular, it is shown that the location of the highest variability of grain size corresponds to that of the beach profile. Also, different grain sizes are shown to exhibit a distinct degree of variability which leads to the conclusion that each sediment size responds to the same hydrodynamics differently.

The temporal eigenvectors determined from the profile and the sediment data shown a seasonal dependency. However, their maxima and minima are not located at the same position. It is shown that this temporal shift is due to the different response of each sediment size to the hydrodynamics, and in particular, that the recovery of the profile starts with fine material from the bar. It is inferred that models for beach profile evolution which do not take into account the sorting processes involved in the sediment transport cannot be fully succesful.

A "master" grain size sample, constructed by adding all the grain samples taken over the profile, is used to further examine the cross-shore redistribution of the sediment. The following working hypothesis is suggested: "For a beach profile within a physiographic unit the master grain size does not depend on time".

1. Introduction

Cross-shore sediment transport has received considerable attention during the last decades. A great number of field experiments and theoretical work have been carried out to describe and evaluate the morphological changes occurring in a beach profile. Most of the recent models for sand transport under combined waves and currents (see Kobayashi, 1988; Wright et al., 1991, as general references) are based on either the energetic approaches of Inman and Bagnold (1963) or Einstein's (1950) traction approach. The refinements to the original models mainly concern the definition of the mean flow and the relative contributions of different oscillatory flows involved in

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the cross-shore sediment transport. The oscillatory flows include incident waves and a wide range of secondary processes at wind-wave frequencies and at low frequencies outside the wind-wave band. Field measurements (e.g. Wright et al., 1991; Osborne and Greenwood, 1992a,b) show that these low frequency flows play an important but not dominant role, on cross-shore sediment fluxes.

Despite the efforts undertaken to adequately model the hydrodynamics of the cross-shore sediment transport formulations, relatively little attention has been focused on the modelling of cross-shore sediment size variation and most of the formulations assume that the grain size distribution or the grain related parameters (D_{50}, w_s) are uniform in the cross-shore direction.

The interrelation between sediment grain size and beach profile morphology is, however, well known. Many field studies have been carried out to investigate the spatial variation along a beach profile of grain related parameters as sample mean, mode and skewness determined from native sand samples (e.g. Krumbein, 1938; Bascom, 1951; Inman, 1953; Miller and Zeigler, 1958; and more recently, Moutzouris, 1991; Stauble, 1992). Also, lab experiments have been conducted in order to simulate the natural redistribution of grain sizes along the profile (e.g. Eagleson et al., 1961; Kamphuis and Moir, 1977).

The temporal trend in sediment grain size distributions is harder to discern than the spatial cross-shore distribution. For this reason, several investigators (e.g. Stubblefield et al., 1977; Davis, 1985; Liu and Zarillo, 1989) suggested that the temporal variations of the surficial sediments were not important. Losada et al. (1992), however, showed that there is a significant temporal structure in the variations of the distribution of sediment grain sizes along the profile.

Attempts have been made to establish a conceptual model to explain and quantify the processes involved in the sorting of grain sizes across the profile (e.g. Bagnold, 1940; Inman, 1959; Zenkovich, 1967; Graf, 1976; and, more recently, Horn, 1991; Liu and Zarillo, 1993). Most of these models are descended from either the null point hypothesis of Cornaglia (1881), or the hypothesis of asymmetrical thresholds under waves (Cornish, 1898). Still, the question remains open and further studies are needed. It is important to note that in order to achieve grain sorting all the models must assume that each sediment size responds to the same hydrodynamics differently as indicated by Ingle's (1966), or Duane's (1970), field experiments.

At present, little is known about the differential grain size response to different processes in space and time (frequency) on the shoreface (Liu and Zarillo, 1993). Field measurements of sediment transport rates are required to solve that differential response.

The present paper is a continuation of the work by Losada et al. (1992). The main goal of this paper is to demonstrate that: (1) the cross-shore sediment distributions along the beach profile are strongly related to the morphological changes in the profile both spatial and temporally; and (2) that different grain sizes have different responses to hydrodynamic processes.

2. Study area and field data

The study site is the beach of "El Puntal", located close to the city of Santander, on the Cantabrian coast of Spain, Gulf of Biscay (Fig. 1). The northern coast of Spain is divided into a series of pocket beaches and small inlets isolated between rocky headlands. Most of the headlands extend into deep water and appear to be effective in confining littoral sand to the embayments. Therefore, the coast can be analyzed as a series of littoral cells. One of these littoral cells is the Bay of Santander. The Bay of Santander is one of the largest on the Cantabrian Coast and provides a natural shelter from the waves of the Gulf of Biscay. For that reason, the bay has been used as a harbor since the 12th Century. The bay is bounded Northward by "El Puntal" Spit, a sandy spit which protrudes well inside the bay (see Fig. 1). More than three-quarters of the deep-water waves, approach "El Puntal" from the northern–northwestern sector. The annual average significant height is about 1 m with typical winter storm waves of $H_s \sim 4$ m. Tides at Santander are semidiurnal with a mean tidal range of 3 m and spring tidal range of 5 m.

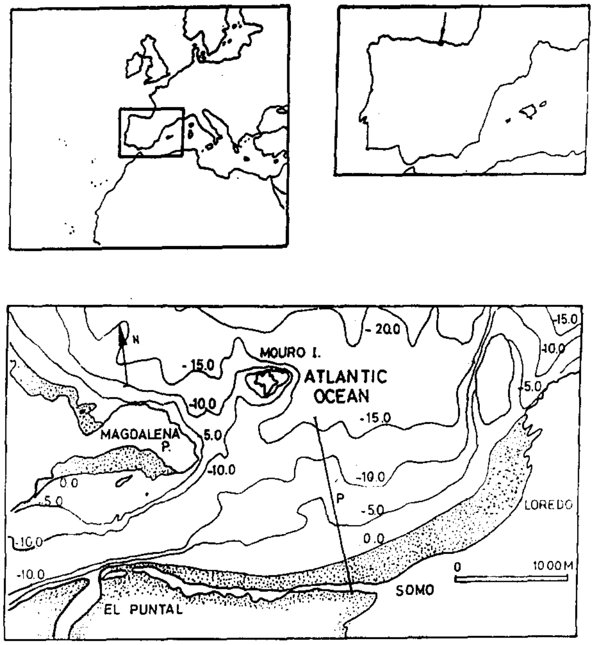

Fig. 1. Location map.

A monitoring project is being carried out to evaluate the evolution of "El Puntal" Spit. The field program includes wave, current and water level measurements, bathymetric beach profiles of the Spit and sand samples. A more detailed description of the monitoring program can be found in the paper by Losada et al., 1991. We will concentrate our work on the beach profile data and sediment sample data collected over a twenty-month period, from May 1990 to January 1992.

2.1. *Profile data*

Profile surveys were taken about once a month during the study period. Each profile was surveyed from mean high water (MHW) on the intertidal beach seaward to a depth of approximately 15 m which extended up to 1500 m. The landward part of each profile was surveyed from permanent monuments landward of the dune to a depth of approximately 1 m. In this way, the seaward part of the land profile overlapped with the shoreward part of the offshore profile. Different profile configurations have been observed at "El Puntal" ranging from: (a) minimal bar feature, with a concave or an "S" profile shape; (b) single inner bar centering around 325 m seaward of the base line.

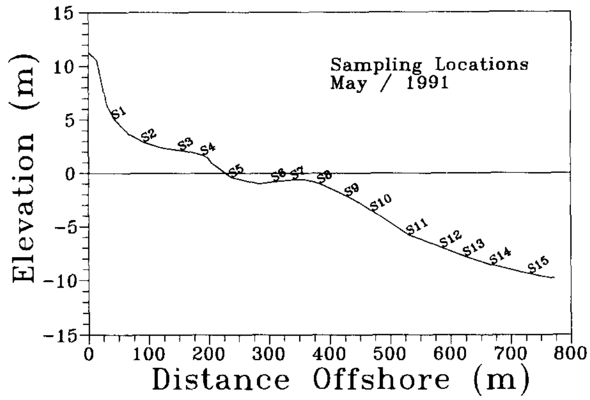

Fig. 2. Sampling location.

2.2. *Sediment data*

Surface grab sediment samples were collected along one profile line (see Fig. 1). All the samples were taken simultaneously with the profile survey. The distribution of sample stations is shown in Fig. 2, along with the mean profile. Sediment samples were collected from 15 positions including the berm and intertidal area, the inner bar and trough area and the nearshore zone. The sampling scheme attempted to locate the sample at the same distance seaward of the baseline during each sampling period. Approximately 300 to 500 grams of sediment were collected and bagged for laboratory analysis. Laboratory procedures consisted of oven drying and sieving according to ASTM standards using ASTM mesh no. 30 (0.59 mm) to no. 200 (0.074 mm). Sediment samples may be classified, in general, as fine well-sorted sand, however, bimodal distributions were found at the bar location during the winter season.

3. Analysis method

In order to objectively separate the spatial and temporal variability of the beach profile data and the sediment grain size data, the principal component analysis (PCA) method was used. The PCA method, also known as empirical orthogonal function (EOF) method, is a technique of linear statistical predictors that has been widely applied in coastal geomorphology. A detailed description of the method can be found in statistics text books (e.g. Daultrey, 1976; Jackson, 1991). In brief, one seeks an eigenfunction expansion of a 2-D data set (e.g. offshore distance, x, and time, t) in the form:

$$y\,(x,t) + \sum_{n=1}^{N} h_n(x) e_n(t) c_n \tag{1}$$

where $h_n(x)$ are eigenfunctions which depend only on x, $e_n(t)$ are eigenfunctions which depend only on t, and c_n are weighing factors. The eigenfunctions are ranked according to the percentage of the variance defined as the mean squared value (MSV) of the data they explain so that the first eigenfunction explains most of the MSV of the data. Thus, a large number of data variables can be efficiently represented by a few (N) empirical functions that describe most of the MSV of the data. This technique has been previously applied to cross-shore beach profile data (e.g. Winant et al., 1975; Aubrey, 1979; Zarillo and Liu, 1988), where water depth was taken as a function of offshore distance and time. Also, the method has been applied to sediment grain size distribution data (e.g. Klovan, 1966; Liu and Zarillo, 1989), where sediment abundance was determined as a function of grain size and offshore distance.

If more than two dimensions were involved, data aggregation or other techniques were used to reduce the problem to a two-dimensional one.

Recently, some techniques have been developed to obtain direct solutions for three-way data sets. These dimensions are often referred to as "modes" and the technique is generally referred to as "three-mode" or "three-way PCA". Procedures of this sort were first proposed by Tucker (1966) and extended by Kroonenberg and De Leeuw (1980) and Ten Berge et al. (1987).

A detailed discussion of the method can be found in Kroonenberg (1983). In brief, the three-way PCA provides a factorization of a three-way data matrix, Z, such that:

$$Z_{ijk}(d,\ x,\ t) = \sum_{p=1}^{s} \sum_{q=1}^{t} \sum_{r=1}^{u} [g_{ip}(d) h_{jq}(x) e_{kr}(t) C_{pqr}] \tag{2}$$

where the coefficients g_{ip}, h_{jq} and e_{kr} are elements of the columnwise orthonormal matrices G, H, E, respectively, and C_{pqr} are elements of the so-called three-mode core matrix, C. The subscripts i, j and k account for the number of points of the data for each dimension (e.g. number of surveys, number of offshore locations ...) and the subscripts p, q and r refer to the pth, qth and rth eigenvector. The matrices G, H and E have similar interpretations to the two-mode eigenvectors and are determined so that the difference between the data and the value obtained from the factorization is minimal according to the mean squared error. The core matrix, C, however, is no longer a diagonal matrix of eigenvalues but a full three-way matrix which describes the basic relations among the variables. If the data exhibit a random variability more eigenvectors (g, h, e) will be needed and, consequently, more combinations of them will be required (C will be a full three-way matrix). If the data have a distinct structure of variability less eigenvectors (g, h, e) will be needed and less combinations of them will be required (C will have more null values). In order to interpret the results of a three-way PCA, we must examine the values of the elements of the three-way matrix, C. Since the eigenvectors are orthonormal (have length one), the elements of the core matrix directly reflect the size of the data, and their squares, C^2_{pqr}, are the contributions to the fit of the model. Obviously, (C^2_{pqr}/total sum of squares) indicates the proportional contribution to the fit, the percentage of explained variation. These percentages can be used to select the number of combinations (p, q, r) needed to represent the data so that a minimum MSV is achieved.

The three-way PCA method has been applied to bathymetric data (Medina et al., 1992; water depth as a function of offshore distance, longshore distance and time) and to grain size distribution data (Losada et al., 1992; sediment retained percentage as a function of grain size, offshore distance and time).

In the present study the two-mode PCA method is applied to the profile data and the three-way PCA method to the sediment grain size distribution data.

4. Results of analysis

4.1. Profile analysis

The onshore and offshore surveys were combined to yield a time series of profiles over the twenty-month period. The data were arranged in the form of a matrix $Y(x,t)$, where Y is the water depth, x the offshore distance (meters) and t time (survey) and standard PCA was performed. A common procedure used in PCA studies (Bartussek, 1973), is to scale each eigenvector with the number of points of its dimensions (x or t) and the squared root of the eigenvalue associated with the eigenvector. The advantage of this scaling is that the eigenvectors, which no longer have length one, are comparable among them and reflect their relative importance according to the MSV they account for.

The spatial and temporal dependence of the first two Bartussek-scaled eigenvectors are shown in Figs. 3 and 4, respectively. The first temporal eigenvector, $e_1(t)$, has an almost constant value (Fig. 4), consequently the combination of the first eigenvectors, $(h_1(x), e_1(t))$, does not depend on time and $h_1(x)$ can be interpreted as a mean profile.

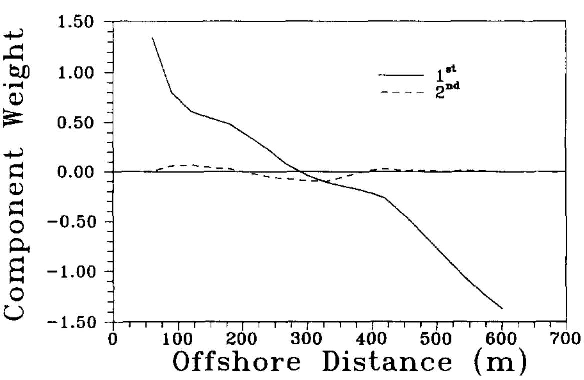

Fig. 3. Profile spatial (offshore) eigenvectors. The first eigenvector is related to a mean profile. The second eigenvector is related to the bar–berm motion of sediment.

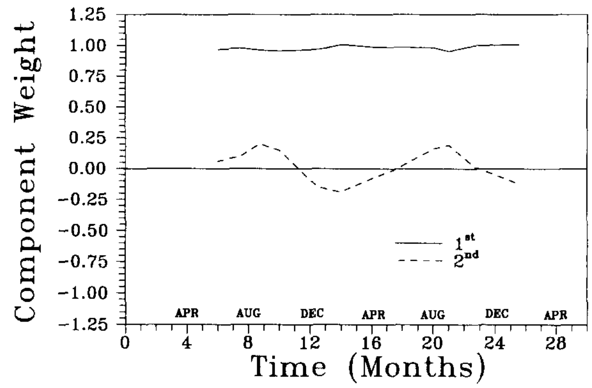

Fig. 4. Profile temporal eigenvectors. Note that the first eigenvector shows an almost constant value and the second eigenvector shows a seasonal dependence.

This mean profile exhibits an S-shape profile with a pronounced terrace at the low tide level position (Fig. 3). These first eigenvectors account for more than 97% of the MSV of the data.

The second temporal eigenvector shows a distinct seasonal dependence, representing the seasonal onshore–offshore movement of sediment. The second spatial eigenvector shows that this seasonal onshore–offshore movement of sediment is mainly bounded within the bar–berm area. The berm and foreshore change along with the bar movement, eroding as the bar is accreting and vice versa. Seawards of the bar, about 500 m from the baseline, the second spatial eigenvector predicts negligible changes. The combination of the second eigenvectors accounts for more than 2% of the MSV of the data.

4.2. Sediment analysis

Sediment grain size data were combined to yield a times series of grain size distributions at different offshore locations along the profile. The data were arranged in the form of a matrix $Z(d,x,t)$, where Z is the sediment abundance (percentage) for a particular grain diameter, offshore location and survey, d is the diameter (millimeters), x is offshore distance (m) and t time. Once the matrix was arranged, three-way PCA was performed. As previously stated, the method obtains matrices G, H and E, which are columnwise orthonormal; in other words, they have length one. The orthonormal eigenvectors of the three-way PCA can be scaled analogously to the standard PCA (Bartussek, 1973); however, when scaling the eigenvectors, the core matrix must also be scaled to leave the model invariant. As in the standard PCA, the advantage of this scaling is that the so determined scaled eigenvectors are comparable within a mode (dimension) and over modes.

The corresponding Bartussek core matrix values and the percentage of variation explained by each element of the matrix are given in Table 1. The total variance explained with the first two temporal eigenvectors, determined by adding all the values of 'explained variation' matrix, is, from Table 1, 97.5% with most of the variance explained with the first combination of eigenvectors (g_{i1}, h_{i1}, e_{k1}). This result is not surprising since we are dealing with raw uncentered data and, consequently, the centroid, defined as some mean of the data, can explain most of the data and is the best candidate for the first eigenvector.

In Figs. 5–7, the first three grain size (g) and offshore distance (h) eigenvectors and the first two temporal (e) eigenvectors are shown. In order to interpret the results of the 3-way PCA, let us concentrate on the first temporal eigenvector (e_{k1}) and the associated offshore distance and grain size eigenvectors.

The first temporal eigenvector shows an almost constant value in time, therefore accounts for a mean (temporal) situation (Fig. 7). The first offshore distance eigenvector is also characterized by an almost constant value (Fig. 5). Consequently, if we use the combination of the first three modes eigenvectors that account for 92.40% of the variance, we obtain a mean grain size distribution in time and in space.

Table 1
Frontal planes of core matrix

Explained variation			Bartussek scaled		
Frontal plane time=1. Down: offshore; across: grain size					
0.9240	0.0000	0.0000	1.060	−0.027	−0.049
0.0000	0.0260	0.0003	−0.027	−4.957	0.782
0.0000	0.0010	0.0068	0.028	−1.442	5.595
Frontal plane time=2. Down: offshore; across: grain size					
0.002	0.0016	0.0003	0.125	1.745	1.171
0.0013	0.0036	0.0025	1.556	13.875	17.072
0.0020	0.0006	0.0049	−2.874	−8.073	−35.762

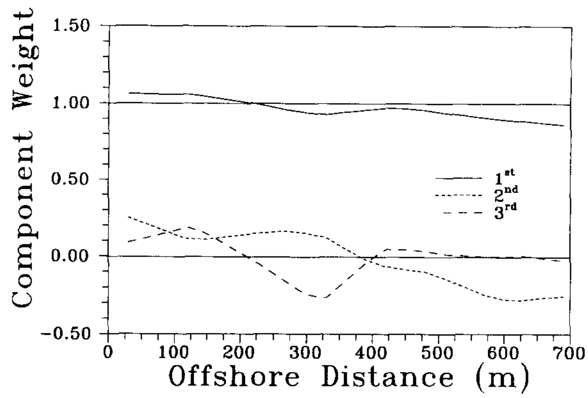

Fig. 5. Grain spatial (offshore) eigenvectors. Interpretation of the different eigenvectors is given in the text. Note the bar–berm variability of the third eigenvector.

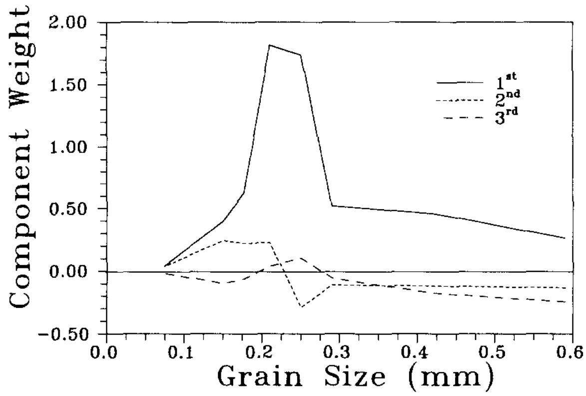

Fig. 6. Grain diameter eigenvectors. The first eigenvector is related to a mean grain size distribution. The second and third eigenvectors are related to the temporal and spatial variability of the mean grain size distribution.

A better representation of the data can be obtained if we add the combination g_{i2}, h_{j2}, which corresponds to the second grain size eigenvector and the second offshore distance eigenvector, that explains 2.60% of the variance. The second grain size eigenvector accounts primarily for the fine sand (has higher values in the fine sand interval) and the second offshore distance eigenvectors shows a decreasing trend with a positive value at the beginning of the profile and a negative value at the end of the profile. When multiplying those eigenvectors with the corresponding Bartussek-

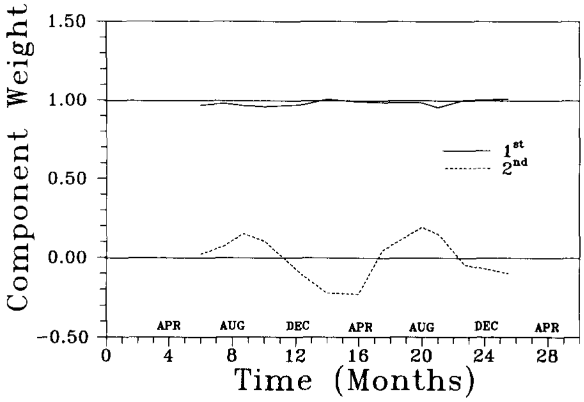

Fig. 7. Grain temporal eigenvectors. Note that the first eigenvector shows an almost constant value and the second eigenvector presents a seasonal dependence.

Table 2
Contribution of the combination (g_{i2}, h_{j2}, e_{k1}) on the combination (g_{i1}, h_{j1}, e_{k1})

Grain size/distance	Combination (g_{i2} h_{j2} e_{k1})				Action over combination (g_{i1} h_{j1} e_{k1})
	Time E	Offshore distance H	Grain size G	Core matrix C	
>0.30 mm >400 m	+	−	−	−	−Substracts >0.30 mm
>0.30 mm <400 m	+	+	−	−	+Adds >0.30 mm
<0.22 mm >400 m	+	−	+	−	+Adds <0.22 mm
<0.22 mm <400 m	+	+	+	−	−Substracts <0.22 mm

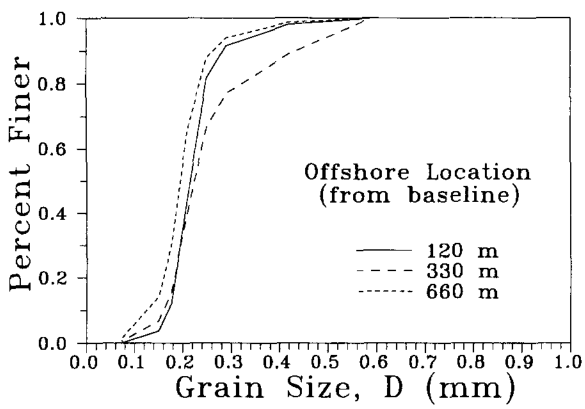

Fig. 8. Grain size distributions at different offshore locations determined by the eigenvector combinations associated with the first temporal eigenvector.

scaled core-matrix value we get a decrease of fine sand at the landward part of the profile and an increase of fine sand in the offshore part of the profile; in other words, we obtain a seaward fining sequence for grain size distribution.

Analogously, more variability of the data can be described using the combination g_{i3}, h_{j3}. That combination adds 0.68% of explained variance and gives information about the coarse sand (g_{i3}), which has negligible variability in the offshore part of the profile and maximum variability in the berm-bar zone of the profile (h_{j3}). With this combination of eigenvectors, we add coarse sand at the bar location and reduce the percentage of coarse sand at the berm area. The final representation of the mean (temporal) situation is composed of an along-profile constant grain size distribution with finer sand in the offshore part of the profile, some coarse sand at the bar location and a well-sorted material at the beach face area (we substract fine and coarse sand). This 'final representation' is just a simplification of the more complex situation described by the complete set of eigenvectors.

A more detailed interpretation of the results can be achieved if the contribution of each combination of eigenvectors within different grain size and offshore intervals is examined. See Table 2 as an example of the contribution (addition or substraction) of the combination (g_{i2} h_{j2} e_{k1}) on the combination (g_{i1} h_{j1} e_{k1}).

In Fig. 8 the grain size distribution determined by using the combinations (g_{i1} h_{j1} e_{k1}), (g_{i2} h_{j2} e_{k1}) and (g_{i3} h_{j3} e_{k1}) is shown for three profile locations: offshore ($x=600$ m), bar ($x=330$ m) and foreshore ($x=120$ m).

The second temporal eigenvector (Fig. 7) shows a seasonal dependency with a maximum in summer and a minimum in winter. The percentage of variance associated with the second temporal eigenvector is 1.7%. Notice that this percentage is on the order of the percentage associated with the seaward fining sequence (2.68%) or the bar coarsening (0.68%). However, the variance is spread

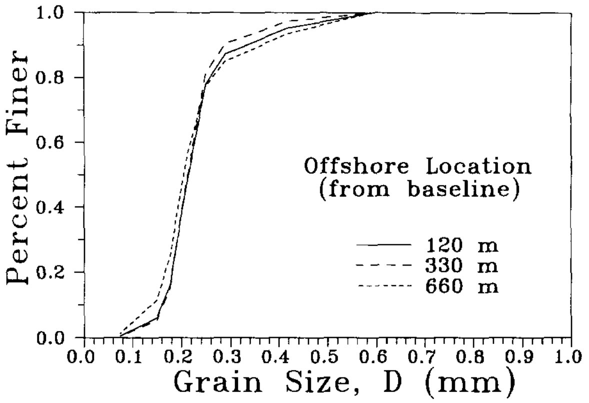

Fig. 9. Grain size distributions at different offshore locations determined by the eigenvector combinations associated with the first and second temporal eigenvectors (summer).

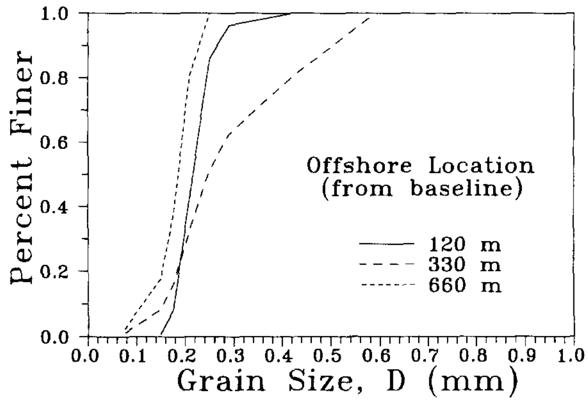

Fig. 10. Grain size distributions at different offshore locations determined by the eigenvector combinations associated with the first and second temporal eigenvectors (winter).

out in several combinations of grain size and offshore eigenvectors (see Table 1) which means a complex variability. Among the nine possible combinations of grain size and offshore eigenvectors, again the pairs (g_{i2} h_{j2}) and (g_{i3} h_{j3}) are the most important in terms of MSV they explain.

Combination $g_{i2}h_{j2}$ indicates a variation of the percentage of fine sand all along the profile depending on the season. In summer, there is an increase, compared with the mean situation, of the percentage of fine sand in the landward part of the profile ($x<400$ m) and a decrease of the percentage of fine sand in the offshore part of the profile, and vice versa in winter.

Combination gi_3hj_3 indicates a variation of the percentage of coarse sand within the bar–berm area. In winter, there is an increase of the percentage of coarse sand at the bar location and a decrease at the foreshore area and vice versa in summer.

The grain size distributions determined by the combinations of the nine pairs associated with the second temporal eigenvector are represented in Figs. 9 and 10. Fig. 9 corresponds to a summer situation and Fig. 10 to a winter situation. Notice that in summer (9) the samples show a very similar distribution, while in winter strong differences occur.

5. Discussion

Many researchers investigating shore-normal grain size variation in the field or in the laboratory have reported on the observed spatial variation of sediment size. As previously stated, there is not always agreement on the trends observed, especially on the trend followed by the degree of sorting across the profile. The results of the three-way PCA may explain some of the discrepancies.

The representation of the data using the combination of the eigenvectors associated with the first temporal eigenvector, which may be interpreted as a temporal mean situation (Fig. 8), shows a grain size distribution along the beach profile similar to that encountered in many beaches (see Komar, 1976, as a general reference). This grain size distribution are: (1) the location of the largest sand particles at the bar-plunge point of the breaker location and a decrease in the grain size both toward deeper water and shoreward across the surf and (2) the swash zone with the finest material in the offshore part of the profile.

Fox et al. (1960) found the poorest sorting in the plunge position. Inman (1953) found the poorest sorting in the breaker and surf zones and the best sorting in the region of the swash zone sands. Bascom (1951) found a decrease in sorting in the offshore direction. On the other hand, Miller and Zeigler (1958) found the highest degree of sorting in the breaker zone, with a progressively poorer sorting both seaward and shoreward. These results must be interpreted with caution since they are obtained from different beaches with different environments and, consequently, the existing sand has a different source. Furthermore, the sorting, usually measured by the standard deviation, is a second moment statistic and is highly dependent on the type of grain size distribution which varies from one beach to another and even within a beach profile.

The degree of sorting in the present study can be evaluated using the grain size eigenvectors. Whenever the second and third grain size eigenvectors, that account for the fine and coarse sand, are added to the first eigenvector the sorting is poorer and vice versa. If only one of the second or third eigenvectors is added (and the other substracted), the sorting may be poorer or better depending on the importance of the eigenvector. The grain size distribution obtained by the mean temporal eigenvectors shows that the sorting is poorer at the bar location and much better in the foreshore area. However, if the seasonal variability is taken into account, it can be observed that in summer (Fig. 9) the degree of sorting is quite similar all along the profile (actually it is slightly better at the bar location) and in winter (Fig. 10) a very poor sorting is found at the bar location. Therefore, the degree of sorting is highly time-dependent (seasonal) and no general assertion can be made using only spatial data.

Besides the information about the grain size and the degree of sorting in the cross-shore direction, the PCA results indicate that grain size distribution variability and beach profile changes are strongly related both spatially and temporally.

5.1. Spatial variability

Observing Figs. 3 and 5, it can be seen that the spatial eigenvectors determined from the profile data and those from the sediment data exhibit similar patterns with their maxima and minima located at the same positions. This spatial relationship between grain size variability and profile shape variability can be clearly observed if the range of variability of both variables at each profile location are examined. In Fig. 11, the annual excursion of the profile depth as well as the mean profile are shown. It is clear from this figure that the maximum variability occurs about 300 m from the base line, at the inner bar location. Seaward

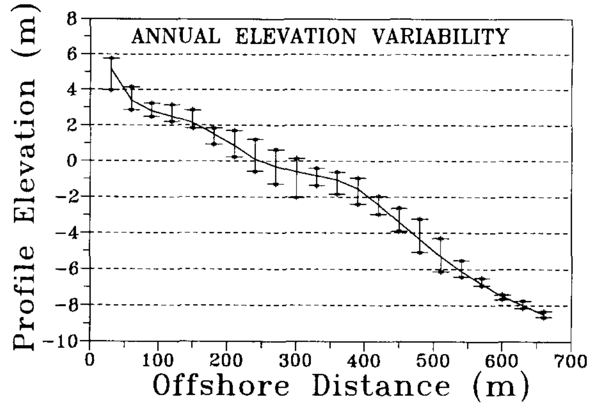

Fig. 11. Annual variability and mean value of beach profile data.

of −8 m depth, about 600 m from the base line, the profile elevations were essentially the same throughout the study. In Figs. 12–14 the annual variability of D_{84}, D_{50} and D_{16} along the beach profiles as well as the mean values of those diameters are shown. The highest variability is shown to occur for the coarser diameters. As expected from the results of the PCA, the location of highest variability of grain size corresponds to that of the beach profile (5).

It is worth noting that if the beach profile changes were due to a mass (bulk) movement of sandy material, the sediment grain size distribution would remain unchanged. Consequently, the beach erosion or accretion is not a mass movement of sand. In other words, each sediment size responds differently to the same hydrodynamics leading to

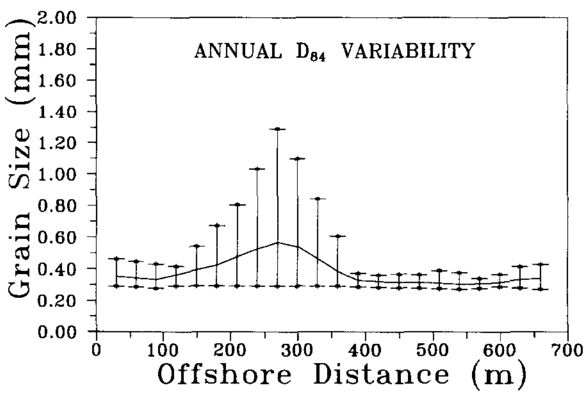

Fig. 12. Annual variability and mean value of D_{84} at different offshore locations.

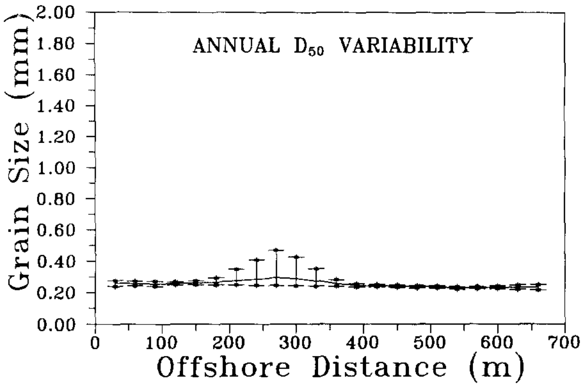

Fig. 13. Annual variability and mean value of D_{50} at different offshore locations.

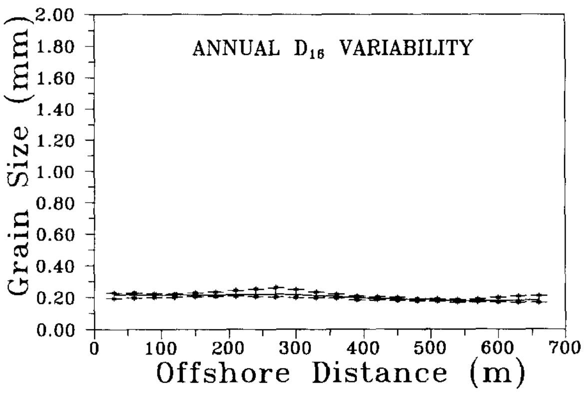

Fig. 14. Annual variability and mean value of D_{16} at different offshore locations.

an important sorting. Therefore, the utilization of statistical parameters such as the mean grain size to represent a sediment sample, as is usually done in sediment transport model, is inadequate. Furthermore, since the grain size distribution, where considerable sorting has taken place, is not even close to log-normal, the usual interpretation of D_{50} may be viewed with caution (e.g. at bar location).

5.2. Temporal variability

Although some investigators suggested that the temporal variations of sediments are not important it is clear from the seasonal dependency of the second temporal eigenvector (Fig. 7) that this is not the case at "El Puntal" Spit. Furthermore, the temporal variability encountered was as important as the spatial one, in terms of MSV (see Table 1).

Changes occurring in the profile shape and sediment distributions are clearly seasonal, and related with the frequency of storm occurrence in the Gulf of Biscay. Observing Fig. 4 it can be seen that it takes about four months to change from the maximum summer stage (September) to the maximum winter stage (January) and about eight months to change from the winter situation to the summer situation. It takes longer for the profile to recover than to erode. Comparing Fig. 4 and Fig. 7, it can be observed that the winter maximum is achieved earlier by the profile eigenvector than by the grain size eigenvector; consequently, the profile is recovering while the sediment is still moving to a "winter situation". That means that the bar is eroding by loosing fine sand and getting coarser; therefore, there is firstly a sand transport of the fine material from the bar location to the berm.

Thus, the sediment transport in the cross-shore direction can be viewed as a sediment or grain size redistribution along the profile. Obviously, the PCA can not give the criteria for that redistribution, but it can determine the modes of variability of that redistribution, both temporal (seasonal) and spatial (bar–berm, offshore–foreshore).

In order to further examine this cross-shore redistribution of the sediment, a "master" grain size sample constructed by adding all the grain samples taken over the profile was obtained for each of the twenty surveys. Fig. 15 shows the

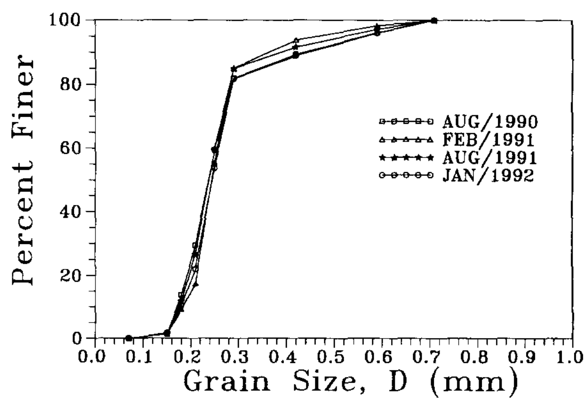

Fig. 15. 'Master sample' grain size distribution.

"master distribution" for the winter and summer surveys. Except for minor deviations, probably due to the discrete sampling technique, it can be observed that the master sample distribution is constant in time. Consequently, the following working hypothesis is suggested:

"For a beach profile within a physiographic unit, the 'master grain size distribution' obtained by adding all samples taken over the active profile does not depend on time".

6. Concluding remarks

Sediment grain size distribution varies markedly along the beach profile of "El Puntal" Spit both spatial and temporally. These variations are shown to be strongly related with morphological changes in the beach profile. Different grain diameters show a distinct degree of spatial variability which leads to the conclusion that each sediment size responds to the same hydrodynamics differently. This conclusion is reinforced by the observation of the temporal variability which showed that the berm recovery is achieved firstly with the fine material from the bar. Consequently, the utilization of statistical parameters such as mean grain size for representing a sediment sample is inadequate if a large interval of diameters is to be represented. Furthermore, models for beach profile evolution that do not take into account the sorting processes involved in the sediment transport cannot be fully successful.

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